ETH zürich

Institute for Mechanical Systems

## PSI Colloquium, May 11, 2023

# Dynamic Gravity: From a crazy idea to high precision measurements

**Jürg Dual**, Emeritus since Aug. 2022

Tobias Brack[1], Fadoua Balabdaoui[2], Stefan Blunier[1], Laura De Lorenzis[1], Jonas Fankhauser[1], Helge C. Hille[1], Stephan Kaufmann[1], Michael Meyer[1,3], Francesco Palmegiano[1], Donat Scheiwiller[1], Jean-Claude Tomasina[1], Pavel Trtik[3], Bernhard Zybach[1]

[1]Institute for Mechanical Systems, Department of Mechanical and Process Engineering, ETH Zurich, Zurich, Switzerland
[2]Seminar for Statistics, Department of Mathematics, ETH Zurich, Zurich, Switzerland
[3]Paul Scherrer Institut (PSI), Laboratory for Neutron Scattering and Imaging, Villigen, Switzerland

# Towards High Precision Measurements of Dynamic Gravity

# Our Gravity Project: Motivation and History (1)

**1991:** First idea of a dynamical transmitter – receiver gravity experiment during preparing the introductory lecture at ETH with the title

"Triumph und Krise der Mechanik"


Dynamical means:

Much higher frequencies than previous experiments (which are "static", mHz)

but remain in near field ( r << $\lambda$=c/f )

What can we measure in the laboratory, which relates to the wave nature of gravity:

- Wave speed and time delay of interaction
- Energy Flow
- Attenuation, Dispersion
- "How long would it take until we realize gravitationally if the moon suddenly would disappear?"

# Our Gravity Project: History (2)

**Ab 1992:** Start of work -> Dissertation of William Walker 1997

Coreferee Walter Kündig, UZH, expert in experimental gravity

Referee JD

**1997:** Preliminary Result: Very difficult experimentally

"Does not make sense, near field, .."

**1998:** Work was abandoned, no funding, William Walker leaves the group

"A project for the time before retirement!"

**2015:** First direct observation of gravity waves generated in outer space by black hole mergers using LIGO und Virgo - two international large scale projects, LIGO alone US$395 million

# Our gravity project: History (3)

- **2018:** Restart of our project in CLA
- **2019:** Start of experiments in Furggels, a former Swiss army fortress

- **March 2021:** First successful fully characterized experiment

  for beam-beam configuration

  Fully characterized means:

  - amplitude and phase response

  - distance behaviour,

  - measure *non gravitational* crosstalk (mechanical, … )

    -> Gravitational constant, “Inverse square law”, ..


# Our gravity project: History (3)

- April 2022: 1st Presentation at APS Meeting

- **August 2022:**

1st paper published in Nature Physics

Huge response!


- December 2022: 2nd Paper submitted
    - In Review with Communications Physics
- April 2023: Presentation at APS Meeting
- **Meeting Nr. 158**!
- **So far:** 14 coworkers, mostly part time
- **Minimal Budget, but much support from ETH and recently a foundation**

# Gravity

- lat. *gravitas*: Weight
- Things with mass or energy are attracted towards one another
- One of the four fundamental forces in nature

| Forces | Range [m] | Relative strength |
|---|---|---|
| Gravitation | $\infty$ | $1$ |
| Elektromagnetism | $\infty$ | $10^{36}$ |
| Weak Interaction force | $< 10^{-18}$ | $10^{25}$ |
| Strong Interaction force | $\approx 10^{-15}$ | $10^{38}$ |

- Fifth Force?? (E. Fischbach, ~1990)

Wikipedia

# History of Gravity

**Antics, Orient**

- Gravity as the reason for free fall
- Foundation for geocentric model of the world

**Kopernikus (1543)**

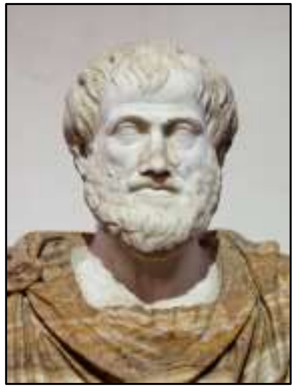
- Also other celestial bodies exert gravity
- → **Heliozentric model of the world**

**Kepler (1609)**

- Each body exerts gravity

**Galilei (beginning of 17th century)**

- First empirical investigations on the free fall



Aristoteles (384 – 322 v. Chr.)

Nikolaus Kopernikus (1473 – 1543)

Johannes Kepler (1571 – 1630)

Galileo Galilei (1564 – 1642)

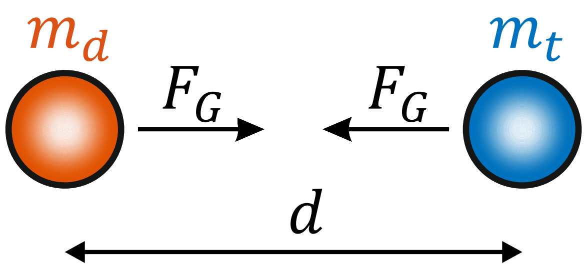
# History of Gravitation – Newton’s theory of gravitation

## Isaac Newton (1687)

- First mathematical description
- G gravitational constant: Big G

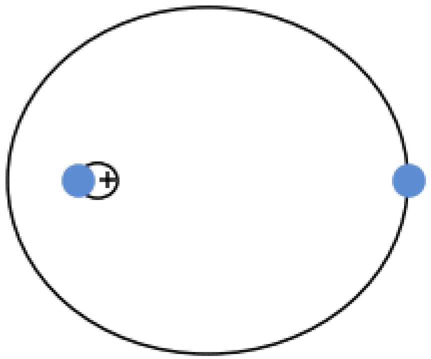
G=6.674 30 x $10^{-11}$ $m^3$ $kg^{-1}$ $s^{-2}$
relative standard uncertainty: 2.2 x $10^{-5}$ (??)

Isaac Newton (1643 - 1727)




$$F_G = \boldsymbol{G} \cdot \frac{m_d m_t}{d^2}$$

- **Consequences of Newtonian Gravity**
  - The action of gravity is instantaneous
  - Allows to model the motion of planets
  - Foundations of classical mechanics
  - $$\boxed{\boldsymbol{g \approx \frac{G m_e}{r_e^2} = 9.81 \frac{m}{s^2}}}$$



# History of Gravitation – Einstein's Theory of Relativity


Albert Einstein (1879 – 1955)

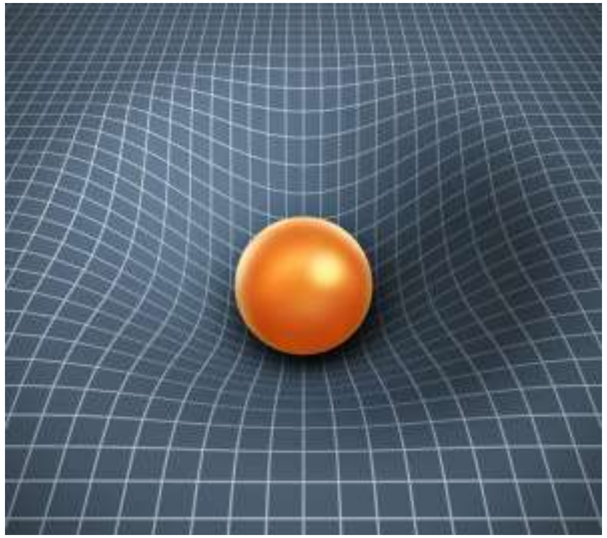
## Special Theory of Relativity SRT (1905)

- Radiation has energy → light has a virtual mass
- Nothing can be faster than the speed of light

$$\boxed{E = mc^2}$$

## General Theory of Relativity GRT (1915)

- New model for gravitation
  - Gravitation is a geometric property of space and time



## Consequences

- Gravitation has infinite range
- Gravitation cannot be shielded
- Existence of gravitational waves

# Summary

## Physical Theories of Fundamental Interactions

**Fundamentale Wechselwirkungen** und ihre Beschreibungen

*(Theorien in frühem Stadium der Entwicklung sind grau hinterlegt.)*

| | Starke Wechselwirkung | Elektromagnetische Wechselwirkung | | Schwache Wechselwirkung | Gravitation |
|---|---|---|---|---|---|
| klassisch | | Elektrostatik | Magnetostatik | | Newtonsches Gravitationsgesetz |
| | | Elektrodynamik | | | **Allgemeine Relativitätstheorie** |
| quanten-theoretisch | Quantenchromodynamik (Standardmodell) | Quantenelektrodynamik | | Fermi-Theorie | Quantengravitation (?) |
| | | Elektroschwache Wechselwirkung (Standardmodell) | | | |
| | Große vereinheitlichte Theorie (?) | | | | |
| | Weltformel („Theorie von Allem“) (?) | | | | |

Gravity separated from everything else!

A unified theory ( theory of everything ) would need to include Gravitation

# Summary Theory of Gravity

## Quantum Theory

- Everything has quantum property: Graviton?? (Hypothetical .. )
- Does not fit to GRT

## Current State

- Numerous modified theories based on GRT: Which one to take?
  e.g. Parametrized Post Newtonian Formalism for weak fields

- Many open questions regarding our understanding of the universe (cosmology)
  - dark matter
  - accelerating expansion of the universe
  - James Webb Telescope: Too big galaxies in the early universe?

- "Mystery of Gravity is deepening" with new G measurements (Physics World 2018)

- What can we learn from a lab experiment in the Near Field? ( $r<<\lambda$)

# Measurement of Gravitation

**Goal**

- Determining the mass of planets (18. – 20. century)
- Confirmation of physical theories (20. century up to now)

**Problems**

- Very weak interaction and forces
- Strong influence of the force of the earth, tides or other nearby masses (constant in time)
- Hidden static masses?

# Measurement of Gravitational Constant G

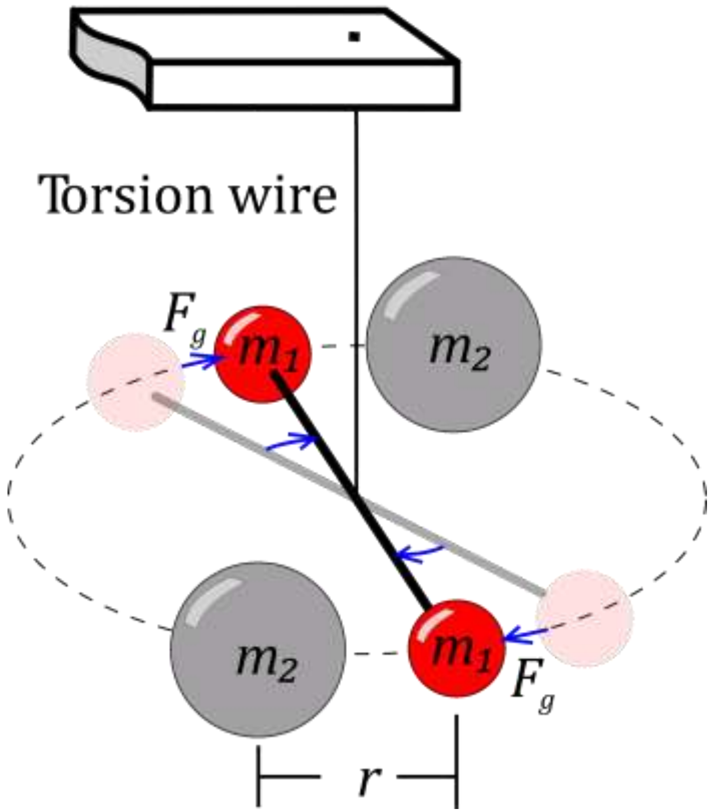
## Torsion Balance

- Developed and used by **Henry Cavendish** (1798)

- **How does it work?** A dumbbell ($m_1$) is rotated by masses $m_2$ measure the equilibrium rotation angle, wire acts as weak spring

  - <u>**Static**</u> Experiment (mHz regime)

- Many improvements
  - Thinner wire, smaller masses (Boys, 1894)
  - Time-of-swing (Eötvös, 1895)
  - Servo-controlled measurements (Michaelis, 1996)
  - …



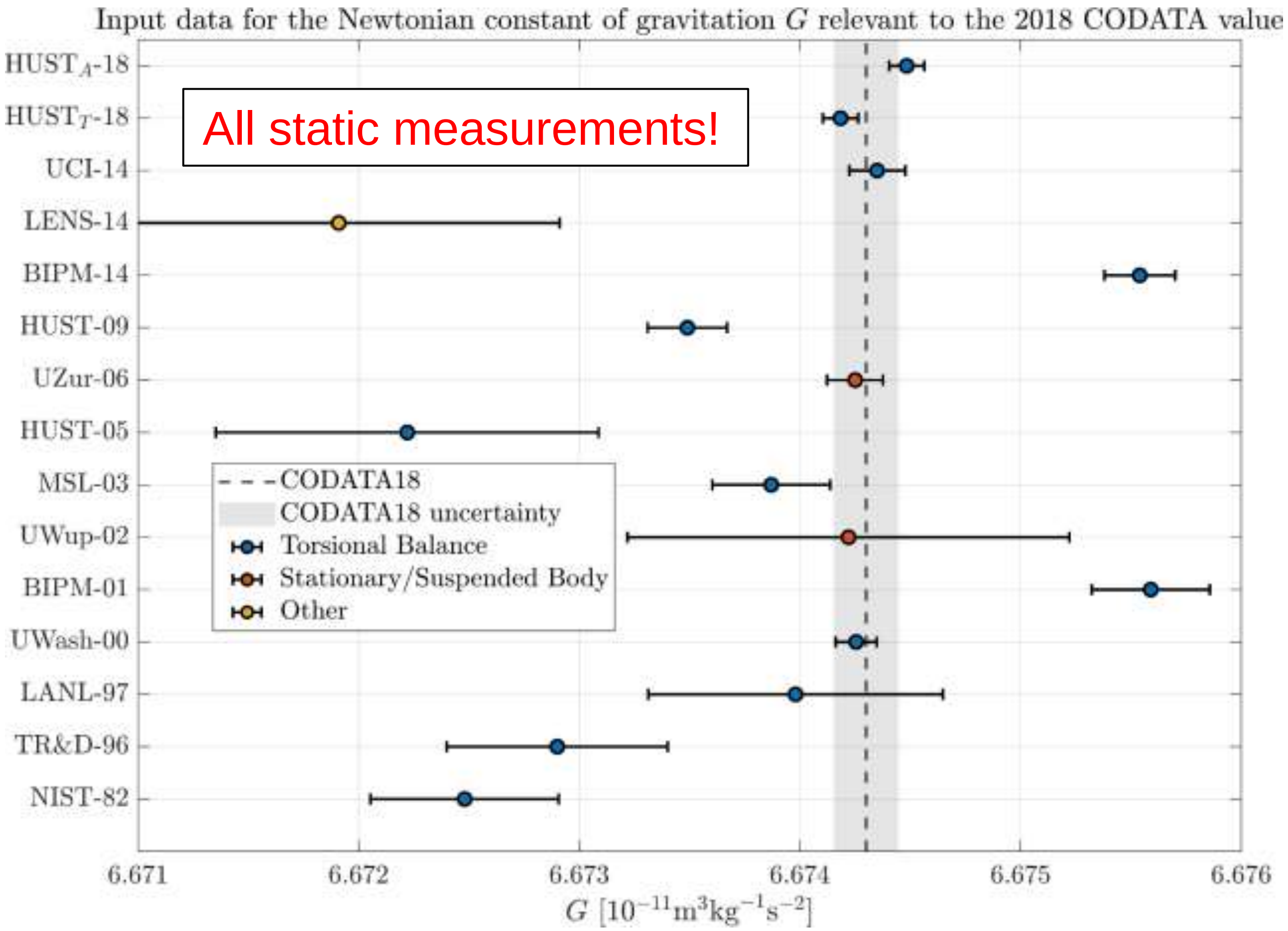
# Static Measurement of Gravitational Coupling

- Easy theoretical description
- More than 200 years of experience
- Flexible design
- State of the art measurement

**Problems/Issues**

- Systematic errors
  - Influence of unknown static masses
  - Ground noise/Temperature instability
- Inaccessibility of dynamics!
- Why Dynamics:
  - Static masses not relevant
  - **Wave nature of gravity:**

    Energy flow, Wave speed, Time delay of interaction, Attenuation (Shielding), Dispersion




Tiesinga, E., Mohr, P. J., Newell, D. B. & Taylor, B. N. CODATA recommended values of the fundamental physical constants: 2018. *Rev. Mod. Phys.* **93**, 025010 (2021).

# Dynamic Measurement of Gravitational Coupling

## Past research

- Sinsky, J. A. Generation and detection of dynamic Newtonian gravitational fields at 1660 cps. *Phys. Rev.* **167** (1968).
- Hirakawa, H., Tsubono, K. & Oide, K. Dynamical test of the law of gravitation. *Nature* **283** (1980).
- Walker, W. D. Gravitational interaction studies. Diss. ETH Zürich **12289** (1997).
- Astone, P. et al. Experimental study of the dynamic Newtonian field with a cryogenic gravitational wave antenna. *Eur. Phys. J. C.* (1998).
- Long, J. C. et al. Upper limits to submillimetre-range forces from extra space-time dimensions. *Nature* **421** (2003).
- Liu Y. et al. Gravitational forces between nonclassical mechanical oscillators. *Phys. Rev. Applied* **15** (2021)
- Ross, M. P., et al. Initial results from the Ligo Newtonian calibrator. Physical Review D, **104**(8) (2021).

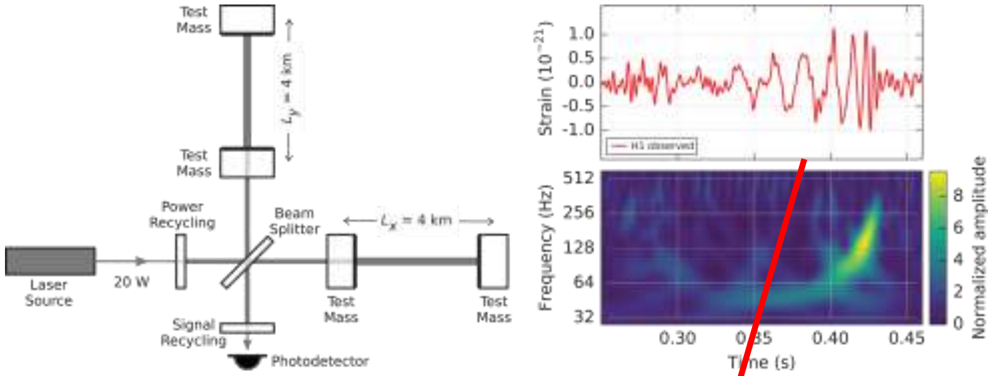



**Figure 1:** Sketch of Laser Interferometer Gravitational-Wave Observatory (LIGO) and the detected signal of event GW150914

35 Hz .. 250 Hz

- mostly distance behavior
  → No fully characterized lab experiment in frequency range > 1Hz

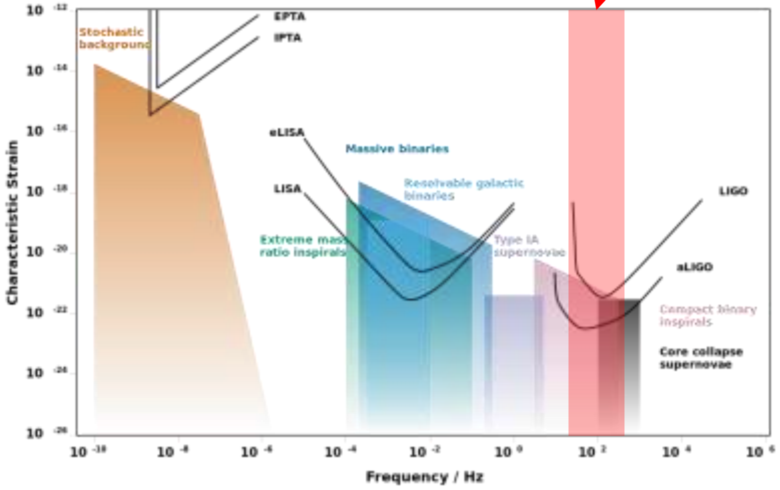


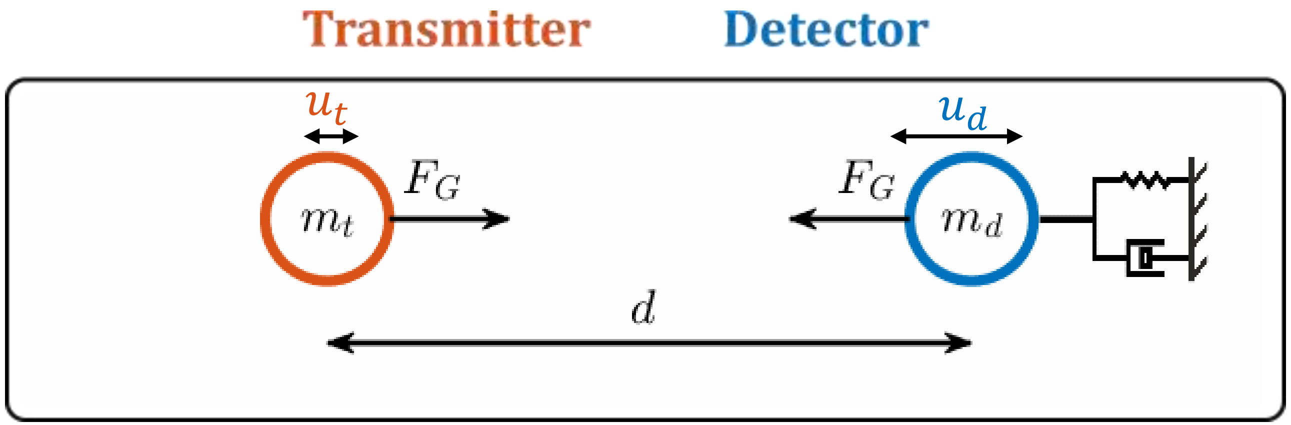

**Figure 2:** Noise curves for a selection of gravitational-wave detectors as a function of frequency.

### Our Goal

- fully-characterized **dynamic** experiment in the lab
- Investigation of gravitation at frequencies ~42Hz
  i.e. at black hole merger frequencies

# Theory of Gravitational Coupling Between Resonators

**Idea:** Periodic excitation force near or at resonance frequency ($\omega_0$) of **detector**




Varying distance $d = d_0 + u_t \sin(\omega t)$

Single Degree of Freedom Oscillator (SDOF):

Amplitude at resonance: $u_d = 2 \cdot \frac{G m_t Q_d}{d_0^3 \omega_0^2} u_t$

**Experimental Realisation**

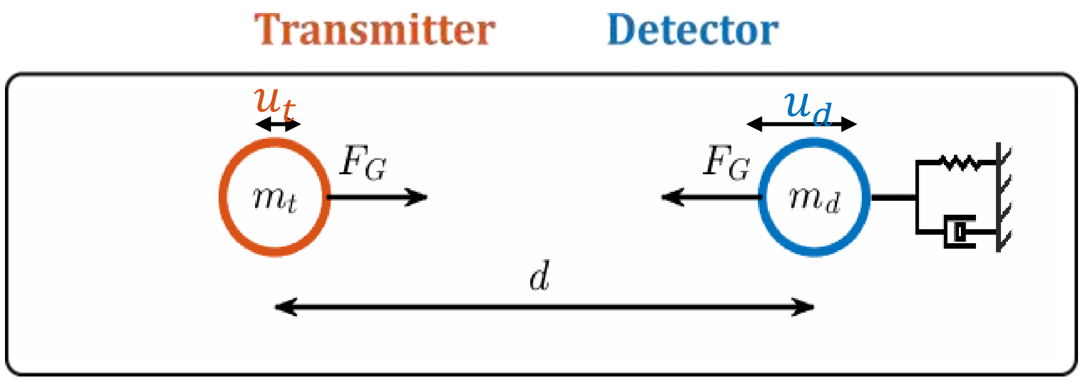
- \+ **Resonant amplification** (high $Q_d \sim 10^4$)
- \+ Decoupling from **static masses**
- \+ **Commercial heterodyne laser interferometers**
- \+ Make use of **dynamic measurement** principles

  Lockin Amplifiers: (BW 3dB = 1.5 mHz)
  Long-term measurement (> 1h per frequency)

- \+ Noise free and temperature stable lab (VC-G)
- \- Theoretical description more complex
- \- Risk of transmission of non-gravitational forces
- ± Amplitude scales with $\frac{1}{\omega_0^2}$ !

# Experimental Realization

$$u_d = 2 \cdot \frac{G m_t Q_d}{d_0^3 \omega_0^2} u_t$$




- Detector: High $Q_d$ (>10^4) beam in first bending resonance suspended at nodes
  -> "low" frequencies at reasonable dimensions

- Transmitter: Need highly stable motion
  ( because of high Q of detector, BW = f/Q, $T_{stationary}$~Q $T_{per}$ )
  - of heavy mass with maximal change of distance between mass elements
  - allows mechanical decoupling
  - at minimal distance

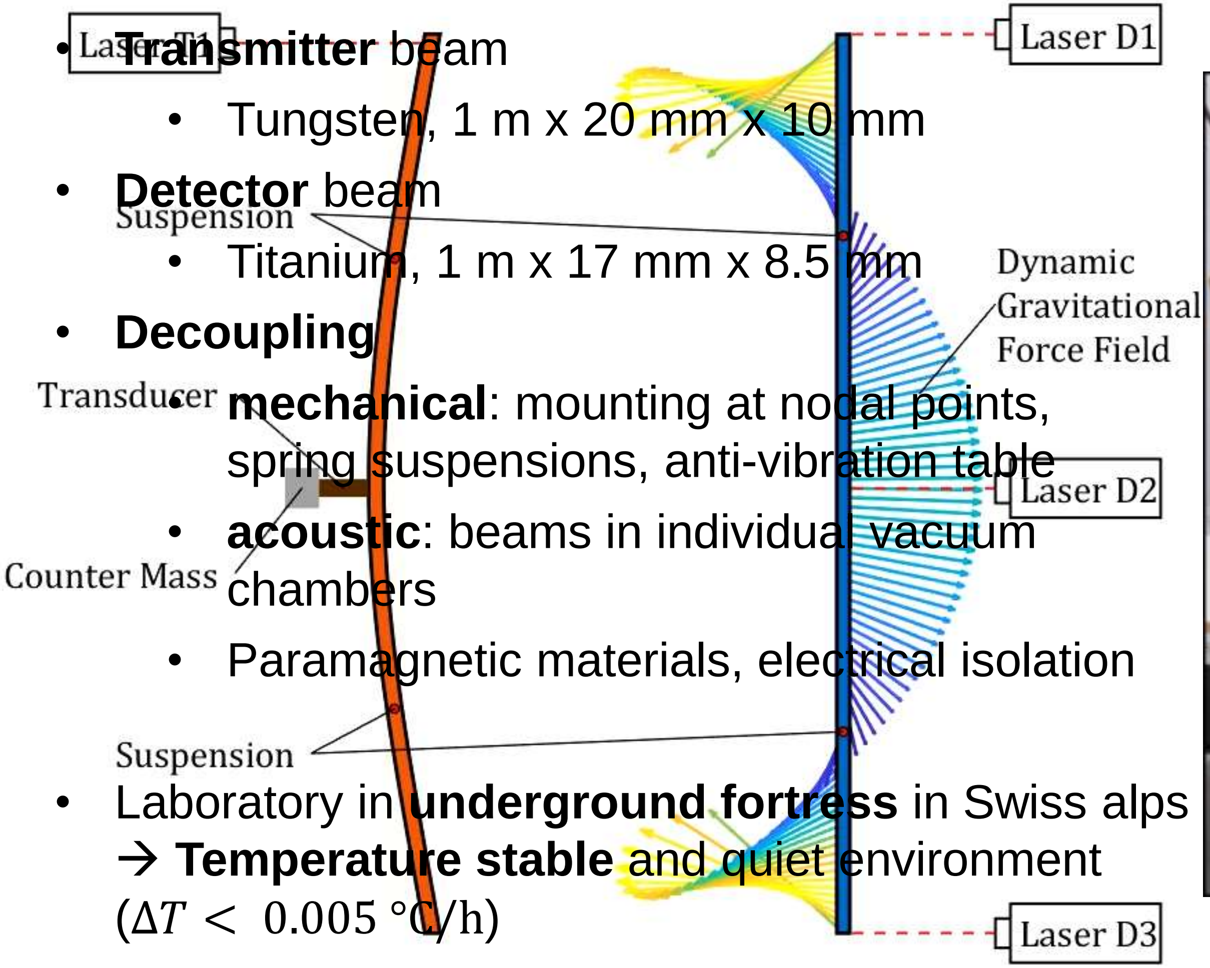
- Set up 1: Parallel beam as transmitter, excited near resonance,
  - suspended at nodes to minimize disturbances, and
  - working against an inertial mass -> internal force as excitation

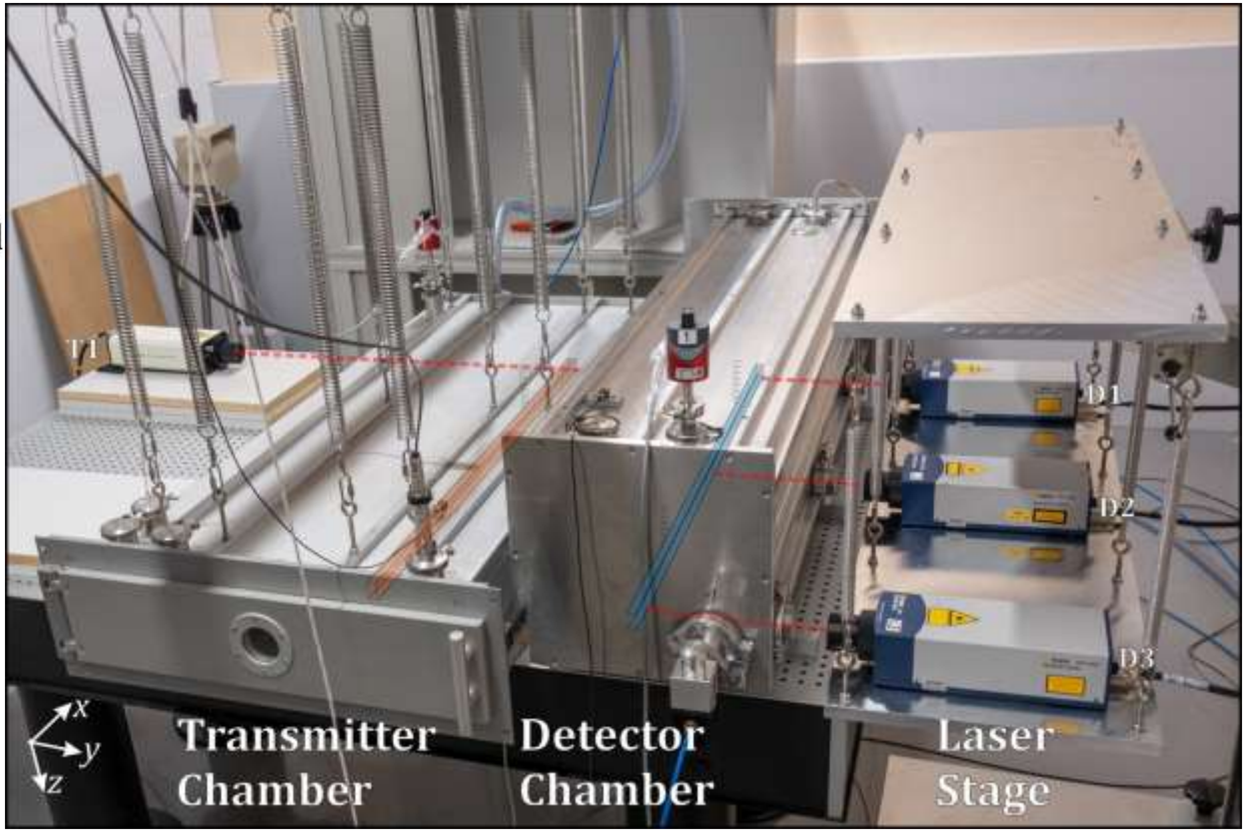
- Setup 2: Two precisely balanced rotating bars
  synchronized to excitation frequency (f/2, f/4, ..)

# Measurement of Gravitational Coupling Between Resonators

## - Setup 1: Two resonating beams at 42 Hz -

- **Transmitter** beam
  - Tungsten, 1 m x 20 mm x 10 mm
- **Detector** beam
  - Titanium, 1 m x 17 mm x 8.5 mm
- **Decoupling**
  - **mechanical**: mounting at nodal points, spring suspensions, anti-vibration table
  - **acoustic**: beams in individual vacuum chambers
  - Paramagnetic materials, electrical isolation
- Laboratory in **underground fortress** in Swiss alps
  → **Temperature stable** and quiet environment
  ($\Delta T < 0.005$ °C/h)



# Measurement of Gravitational Coupling Between Resonators
## - Frequency Response Transmitter vs. Detector -

**Q Factor Design:**

Detector beam: Q large -> amplification

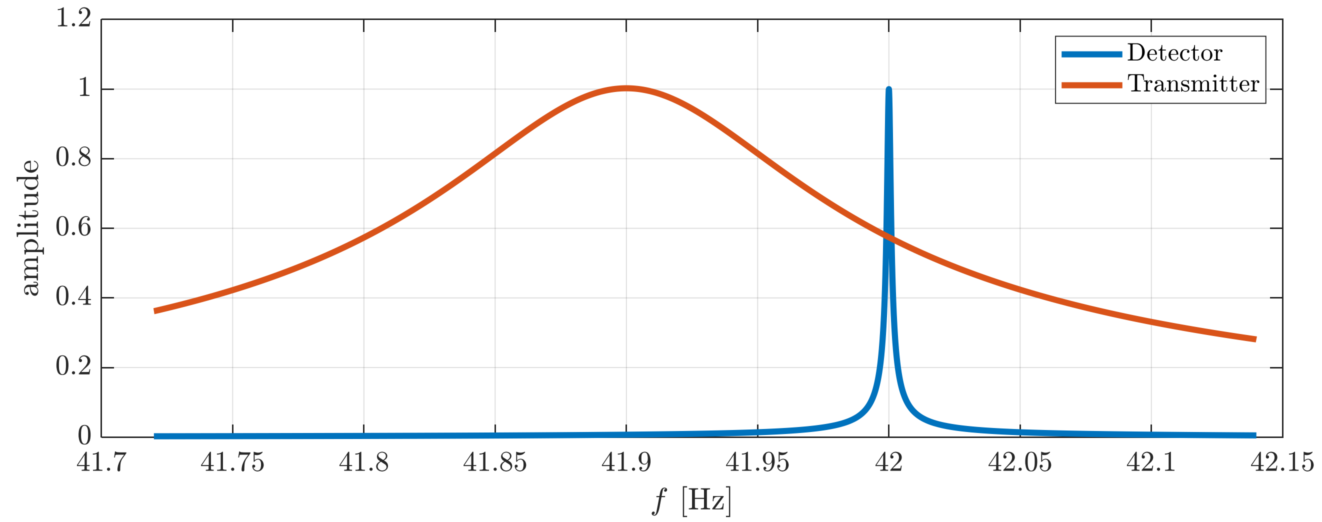
Transmitter beam: medium Q

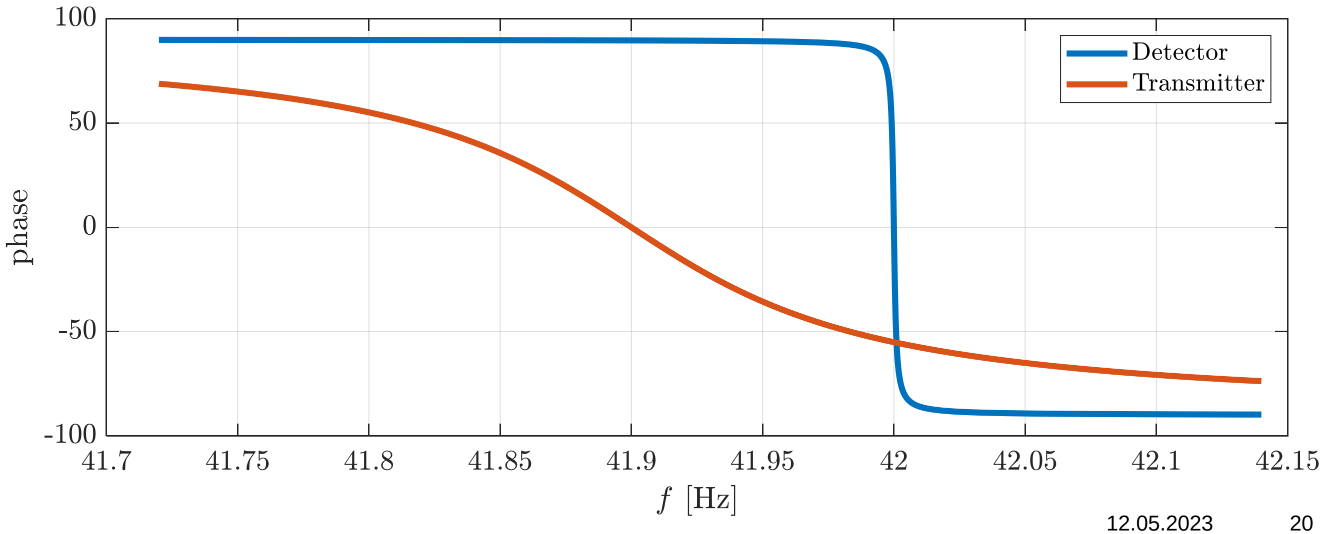
( simplifies tuning ! )

**Measurement**

- Frequency sweep
- Time per frequency defined by:
    - Time constant transmitter
      Q = 300 → 2.5 sec
    - Time constant detector
      Q = 30000 → 250 sec
    - Time constant Lock-In
      8th order lowpass → 500 sec

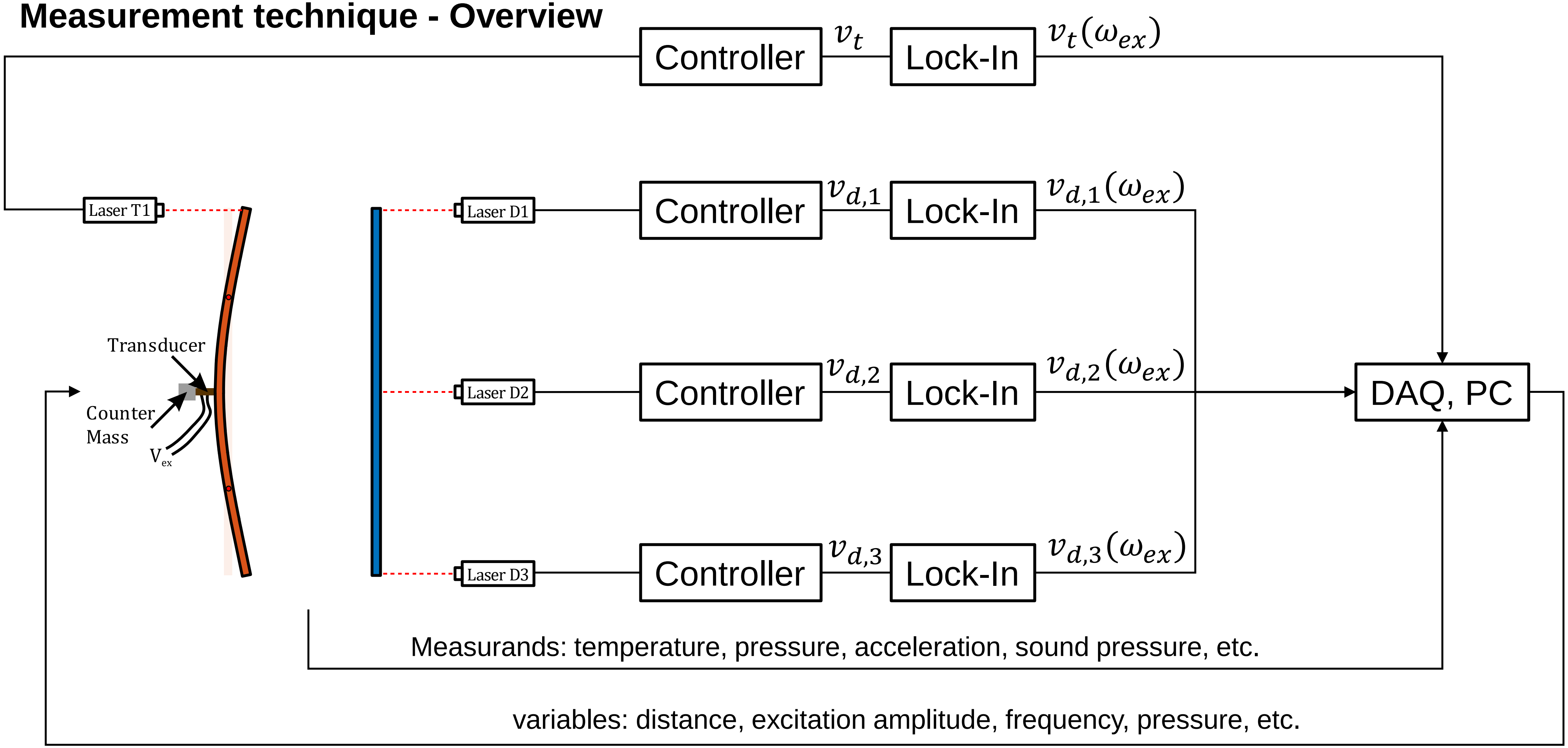
-> Measurement time ~1hr.



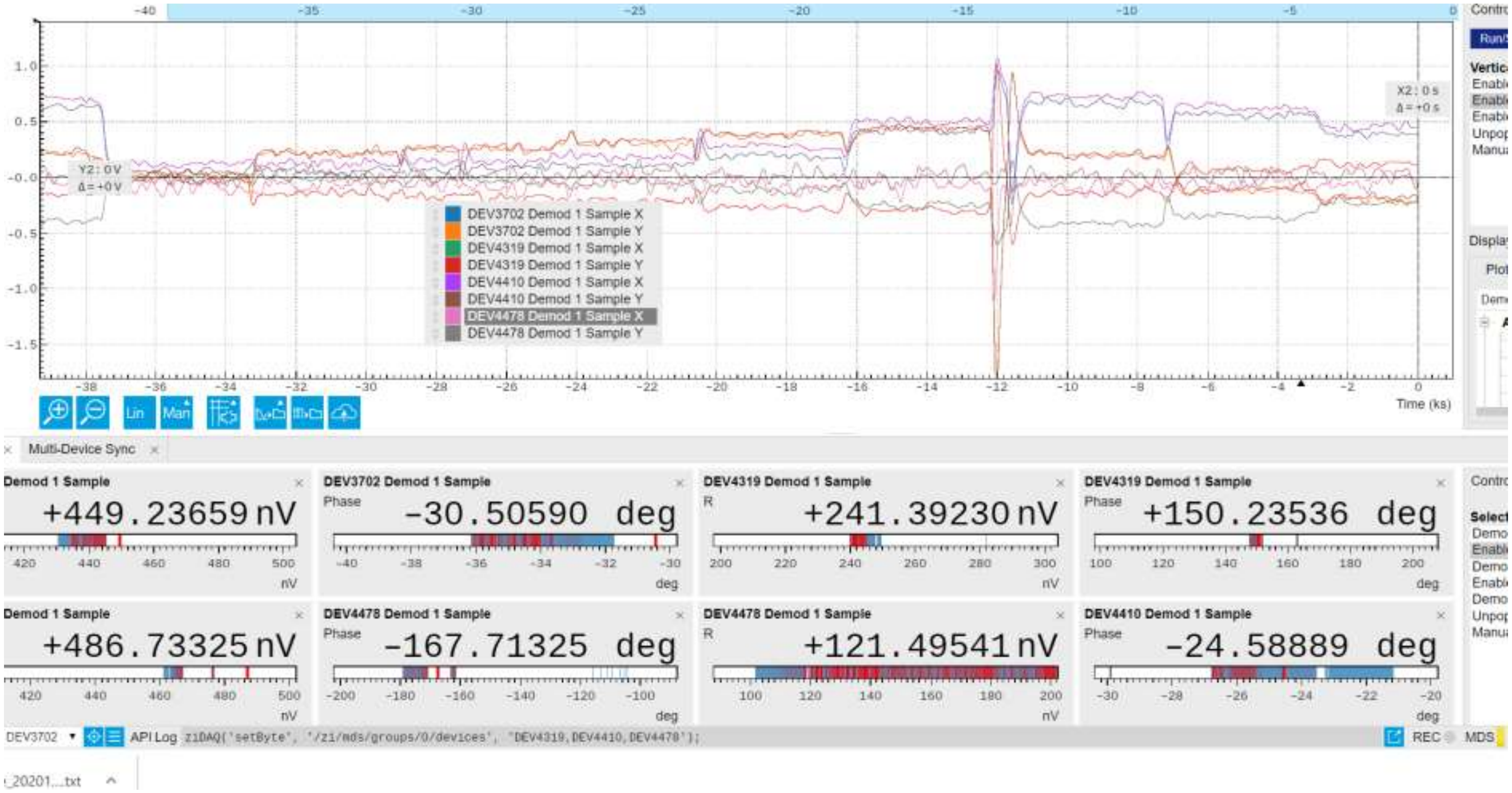



# Measurement of Gravitational Coupling Between Resonators
## - Experimental Setup -

### Measurement technique - Overview



# Raw data: Typical Lockin Signals vs. time



# Why high temperature stability important?

BW at Q=40000:  ca. 1mHz

Temperature dependence of resonance frequency ->

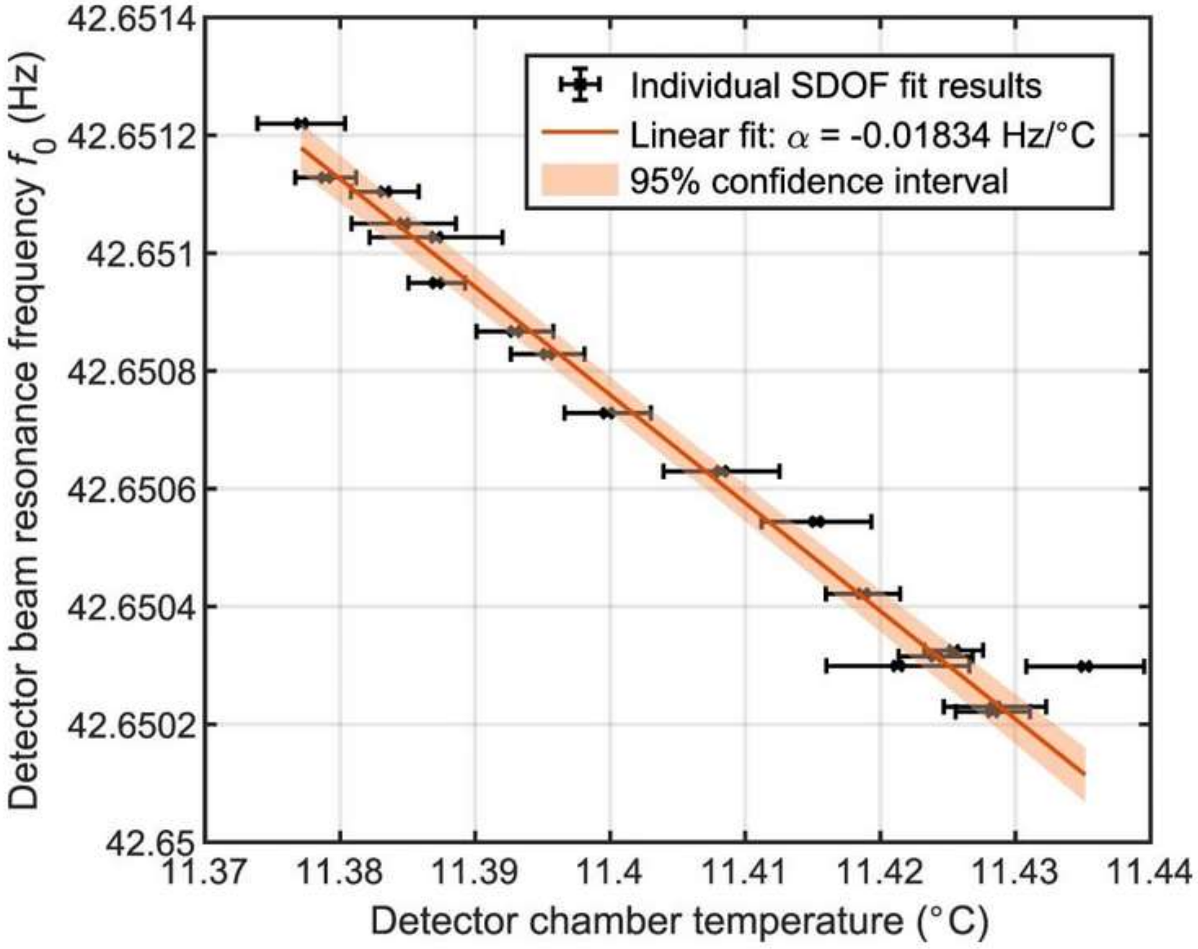
To have a stable measurement point on the resonance curve
We need

$$\alpha \Delta T \ll BW$$

Eg. $\Delta$T=0.01°C -> $\Delta$f=0.18 BW

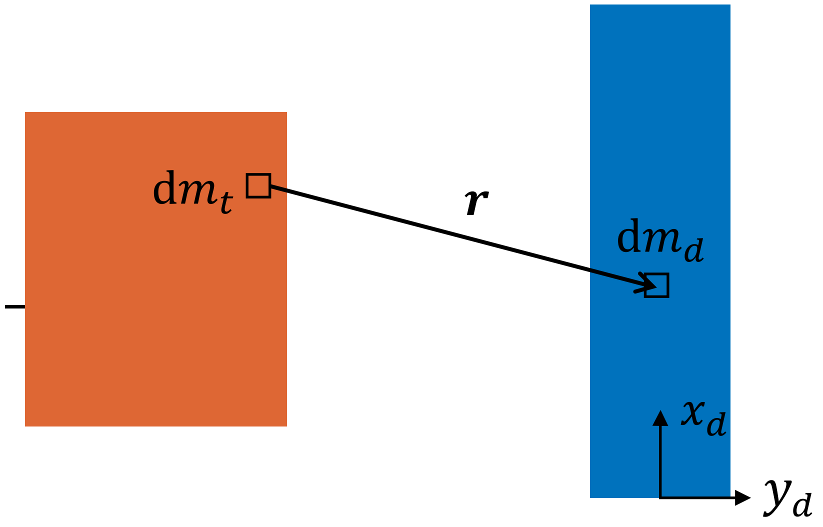
-> Furggels ideal:

High temperature stability
Low mechanical noise




Resonance frequency vs. T for titanium detector beam

# Modelling of Gravitational Coupling Between Resonators
## - Continuum Mechanics -




### Continuum Mechanics (Euler Bernoulli Beam Model)

1. Force between elements $\mathrm{d}m$:

$$\boldsymbol{F}_G^{(\mathrm{d}m_t - \mathrm{d}m_d)} = G \frac{\boldsymbol{r}}{\|\boldsymbol{r}\|^3} \mathrm{d}m_t \mathrm{d}m_d \; ; \; \boldsymbol{r} = \boldsymbol{r}_{\mathrm{d}m_d} -$$

2. Force field as a function of one or several spatial variables

$$\boldsymbol{F}_G(x_d, t) = G \rho_d \rho_t \int_{(V_t)} \int_{(A_d)} \frac{\boldsymbol{r}}{\|\boldsymbol{r}\|^3} \mathrm{d}V_t \mathrm{d}A_d$$

   - time dependent (since $\boldsymbol{r}$ is changing with time), but **non-linear**
   - Can be solved by numerical integration/FEM

3. Model of continuum vibration (detector)
   - Force field as excitation force
     a) Time discrete simulation
     b) Fourier series at $\omega_0$
        Finite elements + analytic

**Calculate displacement at resonance:**

$$u_d(x_d) \approx \mathrm{i} \cdot \frac{G m_t Q_d}{\omega_0^2} u_t \cdot \Gamma(d_0, \text{parameters}) \cdot M(x_d)$$

# Measurement of Gravitational Coupling Between Resonators

- Setup 1: Two resonating beams at 42 Hz -

### Expected amplitudes

- Mass transmitter beam $m_t \approx 4\ \mathrm{kg}$
- Resonance frequency: $\approx 42\ \mathrm{Hz}$
- Chamber pressure: $\approx 1\ \mathrm{mbar}$
- Detector's beam damping: $Q_d \approx 35000$
- Excitation amplitude: $u_t \approx 0.4\ \mathrm{mm}\ \left(0.1\,\frac{\mathrm{m}}{\mathrm{s}}\right)$
- Minimal beam distance: $d_0 = 59\ \mathrm{mm}$

**Detector amplitude** $\boldsymbol{u_d \approx 7\,\frac{\mathrm{nm}}{\mathrm{s}}\,(25\ \mathrm{pm})}$

### Velocity measurement

- Laser Doppler vibrometry (3)
- Lock-in technique (BW 3dB = 1.5 mHz)
- Long-term measurement
  (30 frequencies,ca. 1h per frequency)
- Noise free lab (VC-G)

**Resolution** $\boldsymbol{\approx 0.16\,\frac{\mathrm{nm}}{\mathrm{s}}\,(0.6\ \mathrm{pm})}$

Note: 1nm=0.000001mm, 1pm= 0.001nm

# Dynamic Measurement of Gravity – Data Evaluation

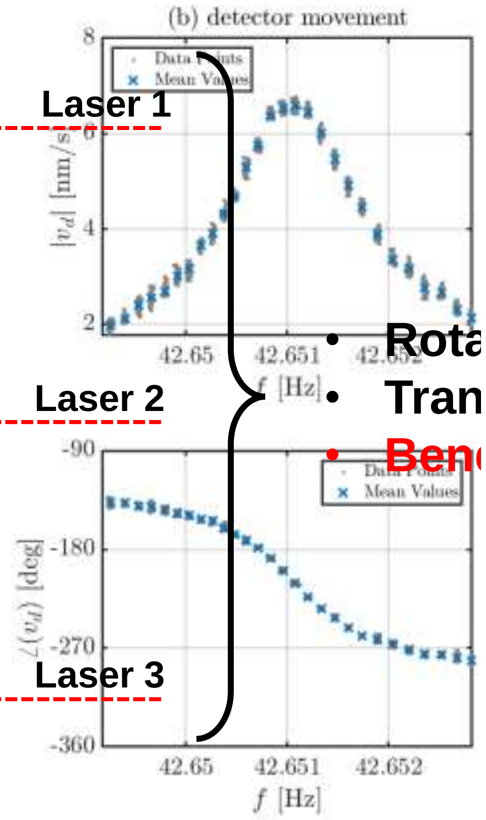
**Frequency Sweep (ca. 30 Frequencies, 30h)**

- Extract Bending Motion $u_d$
- Calculate transfer function $\frac{u_d}{u_t}$
- Fit transfer function of SDOF system
- $$\frac{u_d}{u_t} = \frac{\mathrm{i}\omega \cdot A_0 \cdot \frac{\omega_0}{Q}}{-\omega^2 + \frac{\omega_0}{Q} \cdot \mathrm{i}\omega + \omega_0^2} \cdot e^{i\varphi_0} (+XT)$$

  $\rightarrow \omega_0, Q, A_0, \varphi_0$

- Theory yields $G$ as a function of $d$

  $A_0 \sim \frac{G m_t Q_d}{d_0^2 \omega_0^2}$ at resonance




Bending

# Gravitational Coupling Between Resonators (Beam –Beam Configuration)

**Distance variation** (59 mm .. 120 mm)

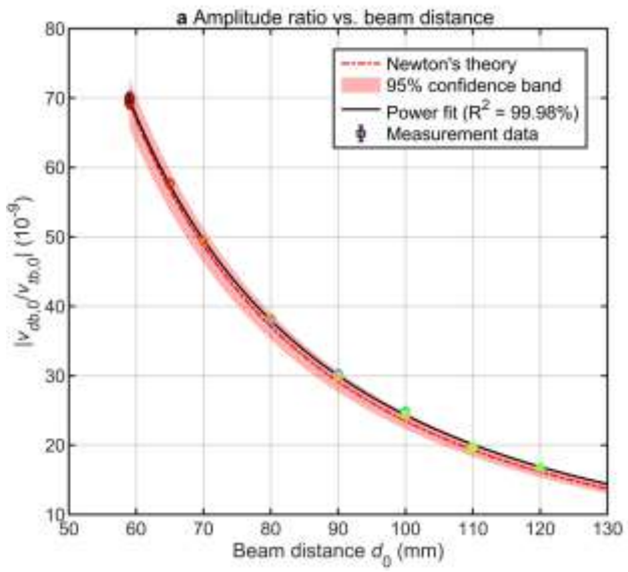
- Distance behavior $\sim \frac{1}{d_0^2}$
- Agreement with theory **within 2-3%**

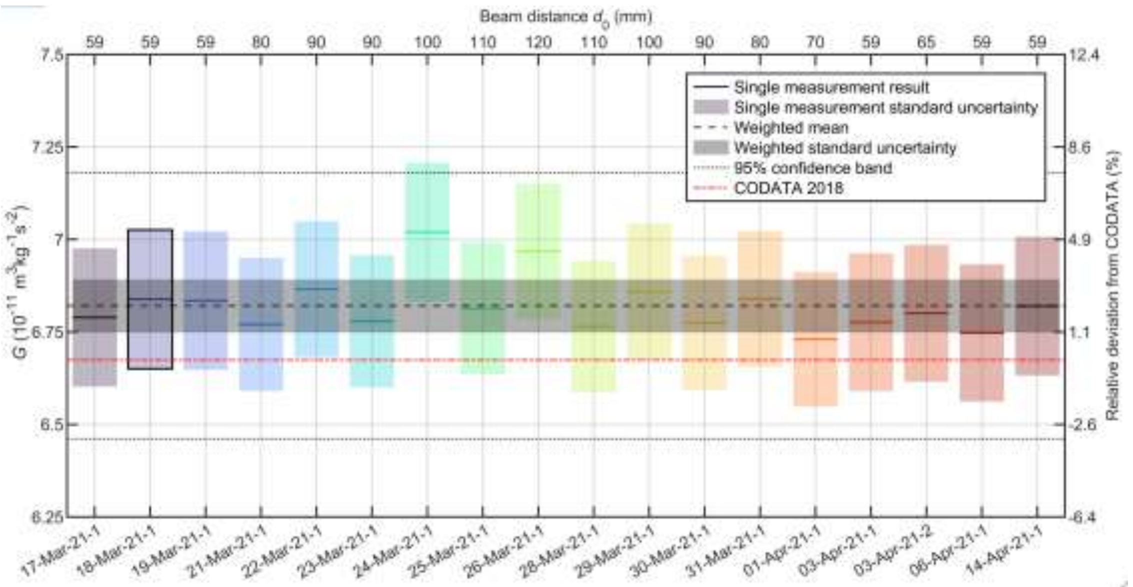
For the **first time** we achieved

- Derivation of ***G*** from **dynamic experiment at frequencies $10^4$x higher** than in established, static experiments

$$\boldsymbol{G} = 6.825(75) \cdot 10^{-11} \frac{\mathrm{m}^3}{\mathrm{kg\ s}^2}$$

- Quantify **energy flow** due to gravitation ($10^{-20}$ W at 59 mm)
- Results published in ***Nature Physics, 2022 incl. News and Views Article***



# Dynamic Gravity First Paper

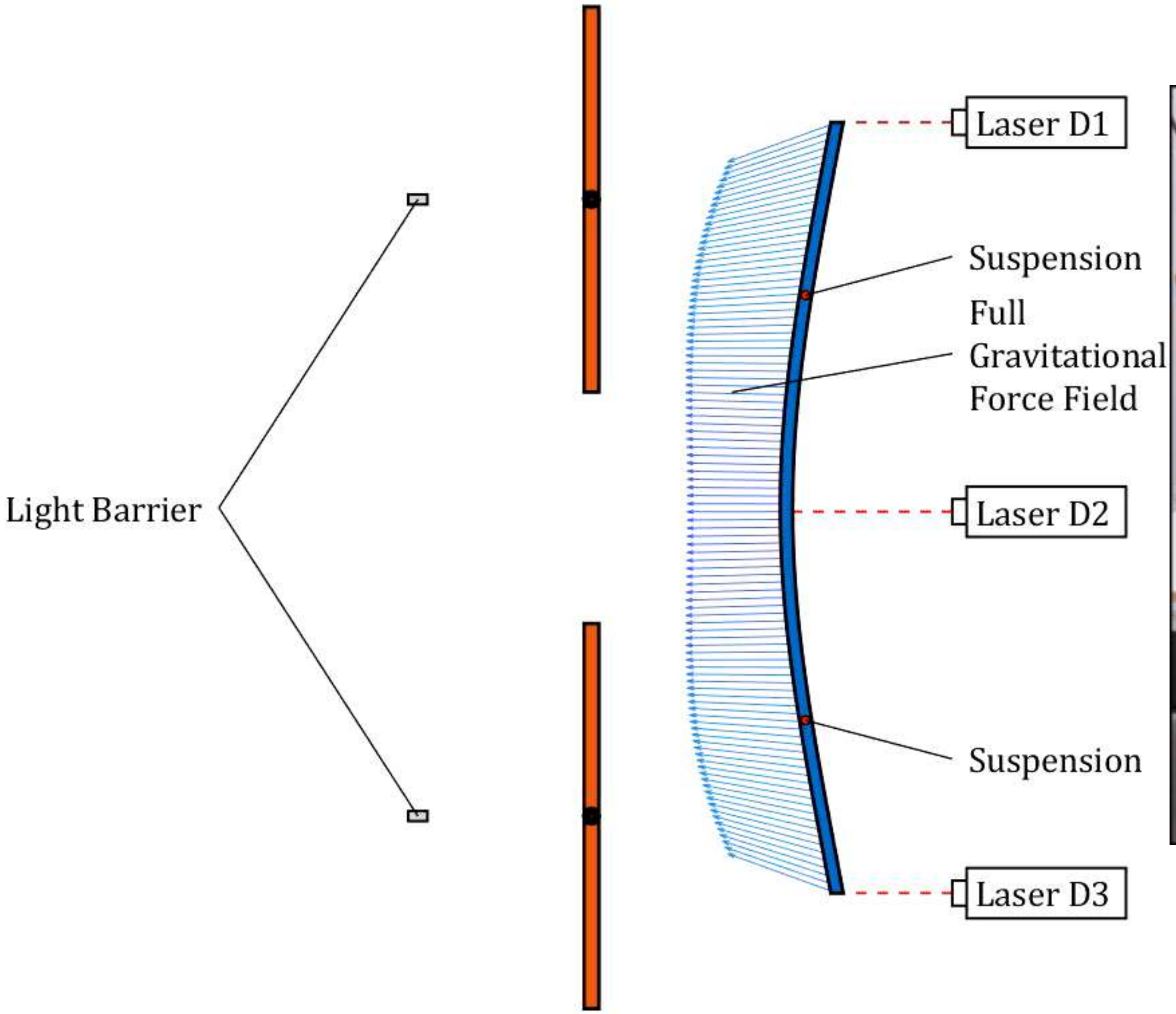
## Publications

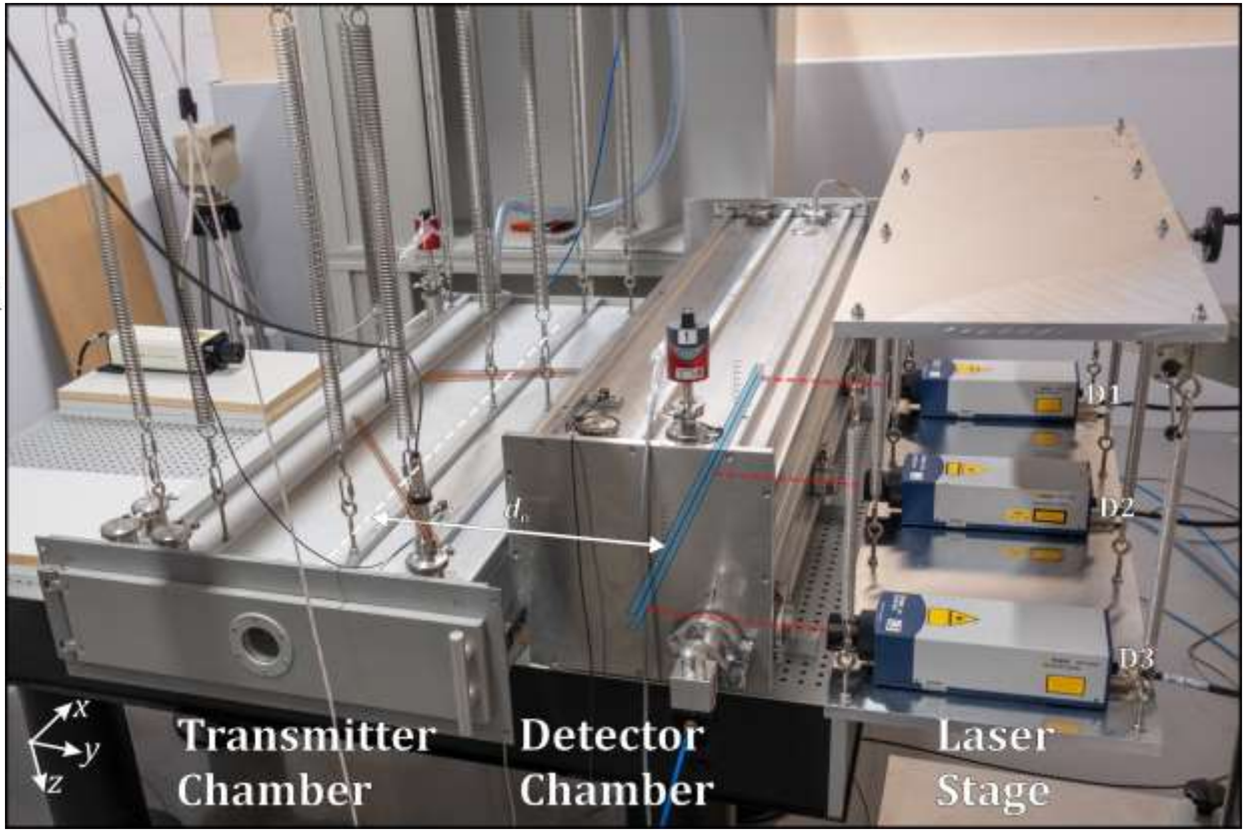
- Brack *et al.* Dynamic measurement of gravitational coupling between resonating beams in the hertz regime. *Nat. Phys.* **18**, 952–957 (2022). https://doi.org/10.1038/s41567-022-01642-8

- Rothleitner, C. Good vibrations. *Nat. Phys.* **18**, 856–857 (2022). https://doi.org/10.1038/s41567-022-01646-4
- An unconventional strategy sizes up Newton's 'big G', *Nature* **607**, 424 (2022) https://www.nature.com/articles/d41586-022-01911-9
- Schirber, M. Bending under Big G. *Physics* **15**, 121 (2022) https://doi.org/10.1103/Physics.15.121
- Plus numerous accompanying articles in media

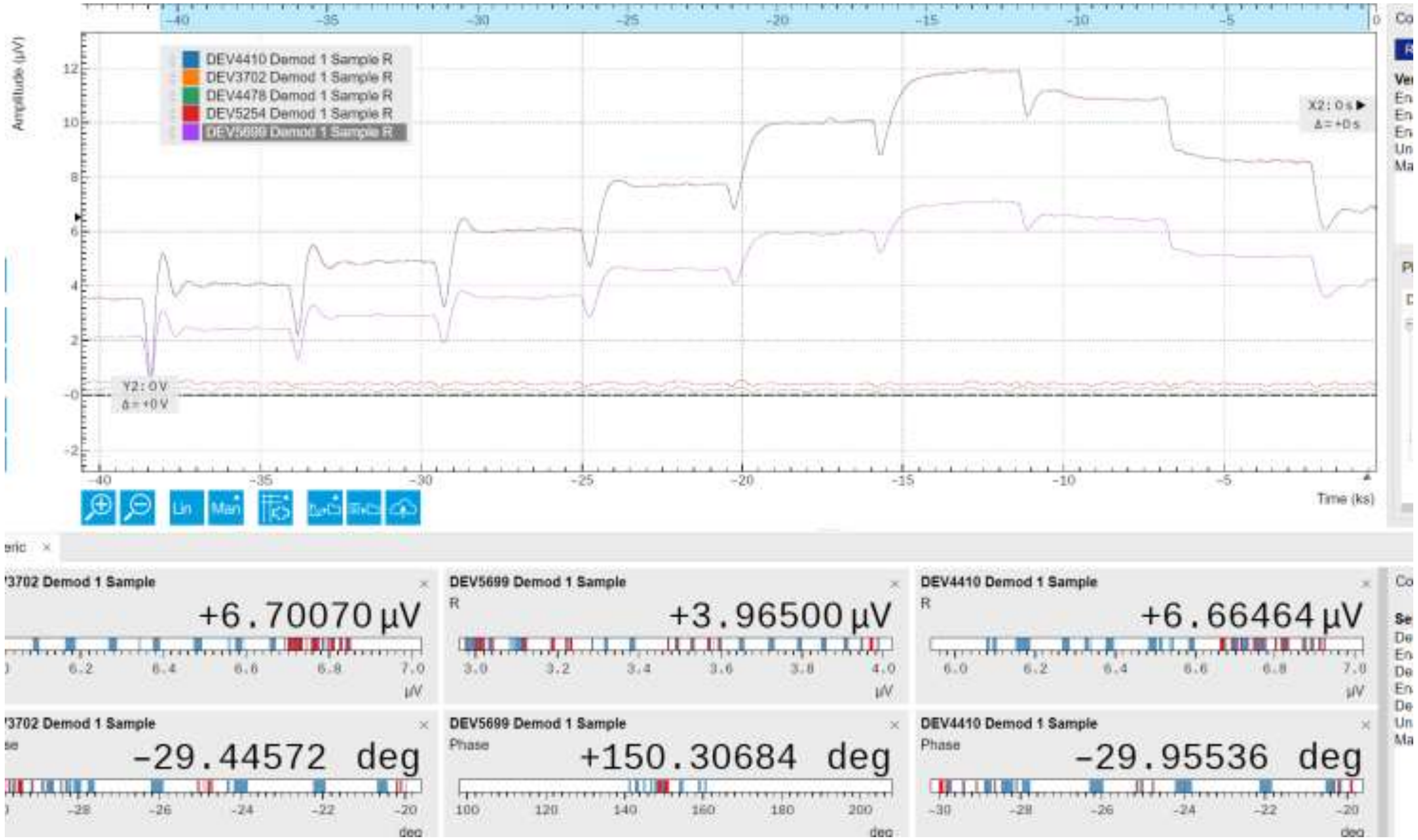
# Measurement of Gravitational Coupling Between Resonators

## - Setup 2: Two Rotating Bars Excite Bending Resonance -

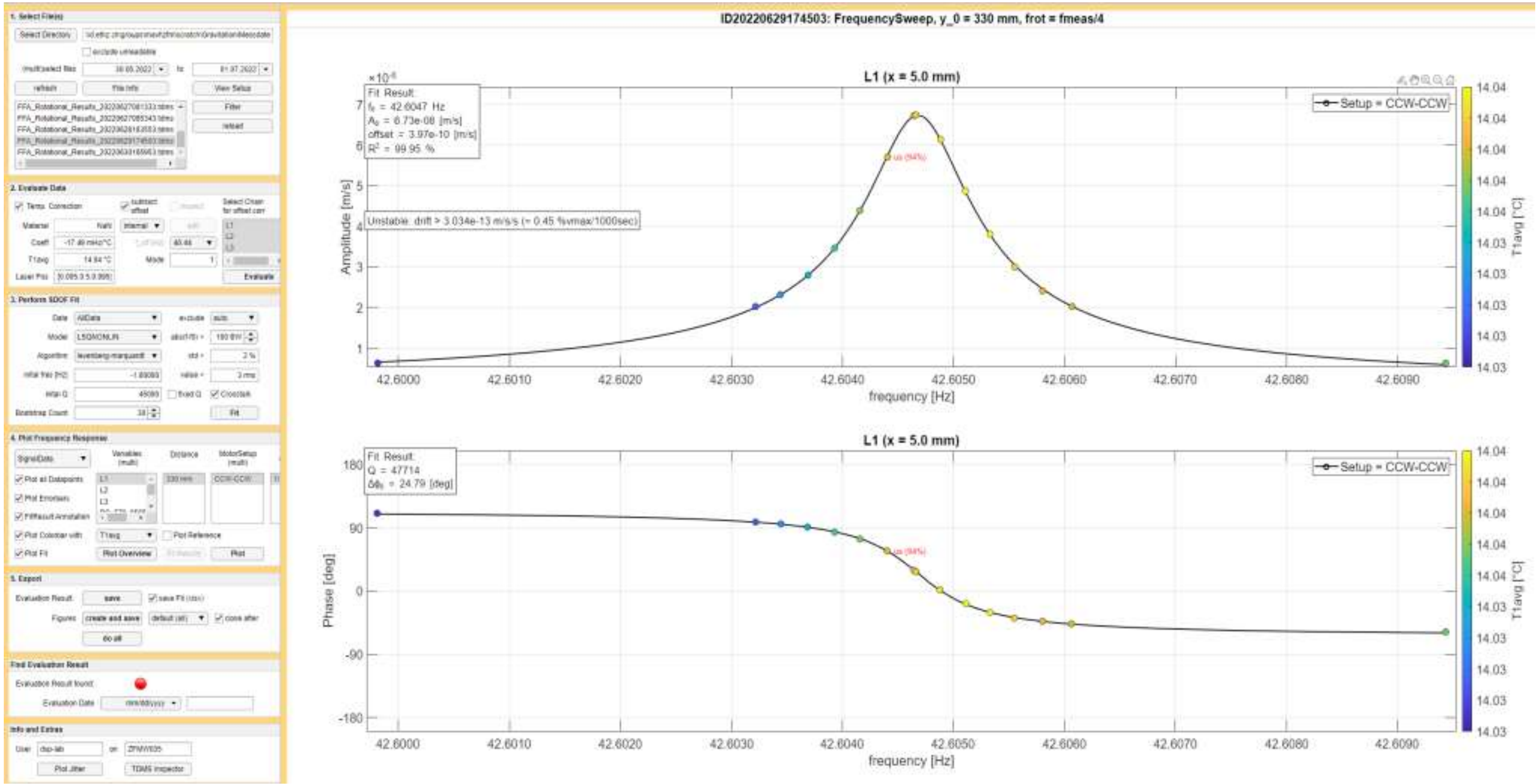


# Measurement of Gravitational Coupling Between Resonators



# Measurement of Gravitational Coupling Between Resonators



# Theory Excitation of Detector Beam by two Rotating Bars

Nonstandard moving load problem: Known from trains on bridges!

Non separable loading of partial differential equation

Classical Book by L. Fryba: Vibrations of Solids and Structures under Moving Loads

Here:

Distributed loading

Variable force distribution

Variable speed of load

Speed close to wave speed

Periodic

Solve by normal mode expansion

Or by FEM

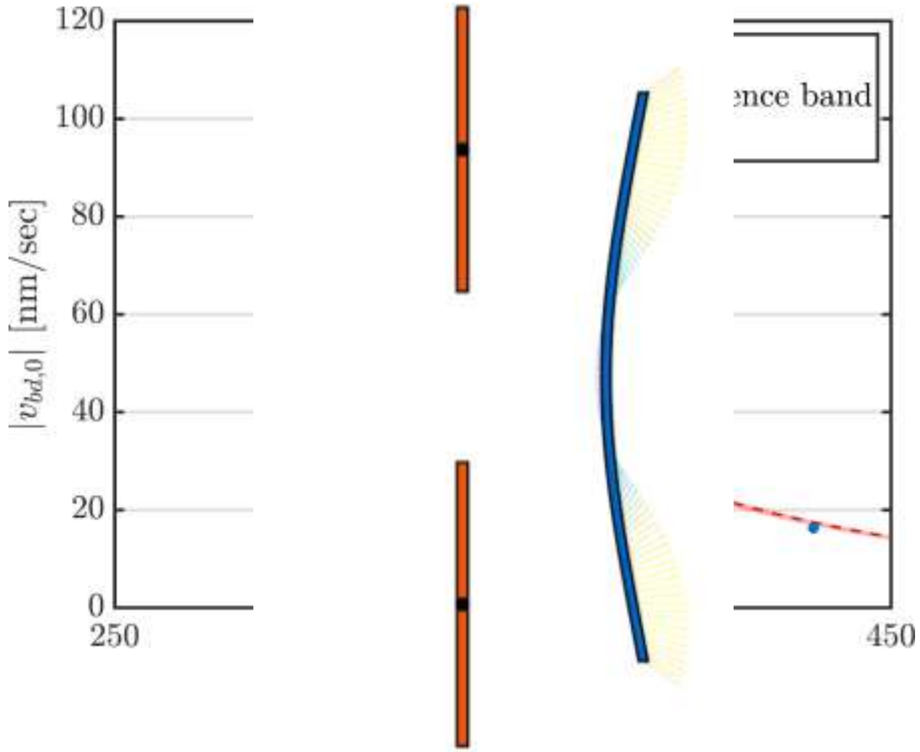
To yield stationary solution

# Measurement of Gravitational Coupling Between Resonators

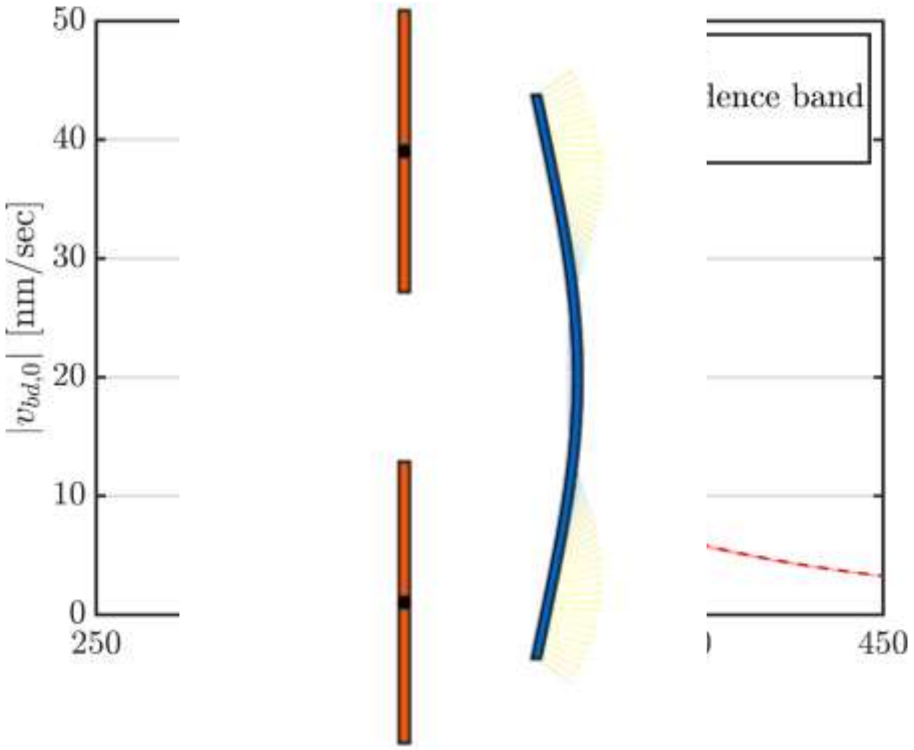
## - Setup 2: first results -

- Custom made motor synchronization ($\Delta\phi < 0.01$ deg)
- Chamber pressure $\approx 0.02$ mbar

### Second harmonic: $\omega_{\text{rot}} = \frac{\omega_{\text{res}}}{2}$

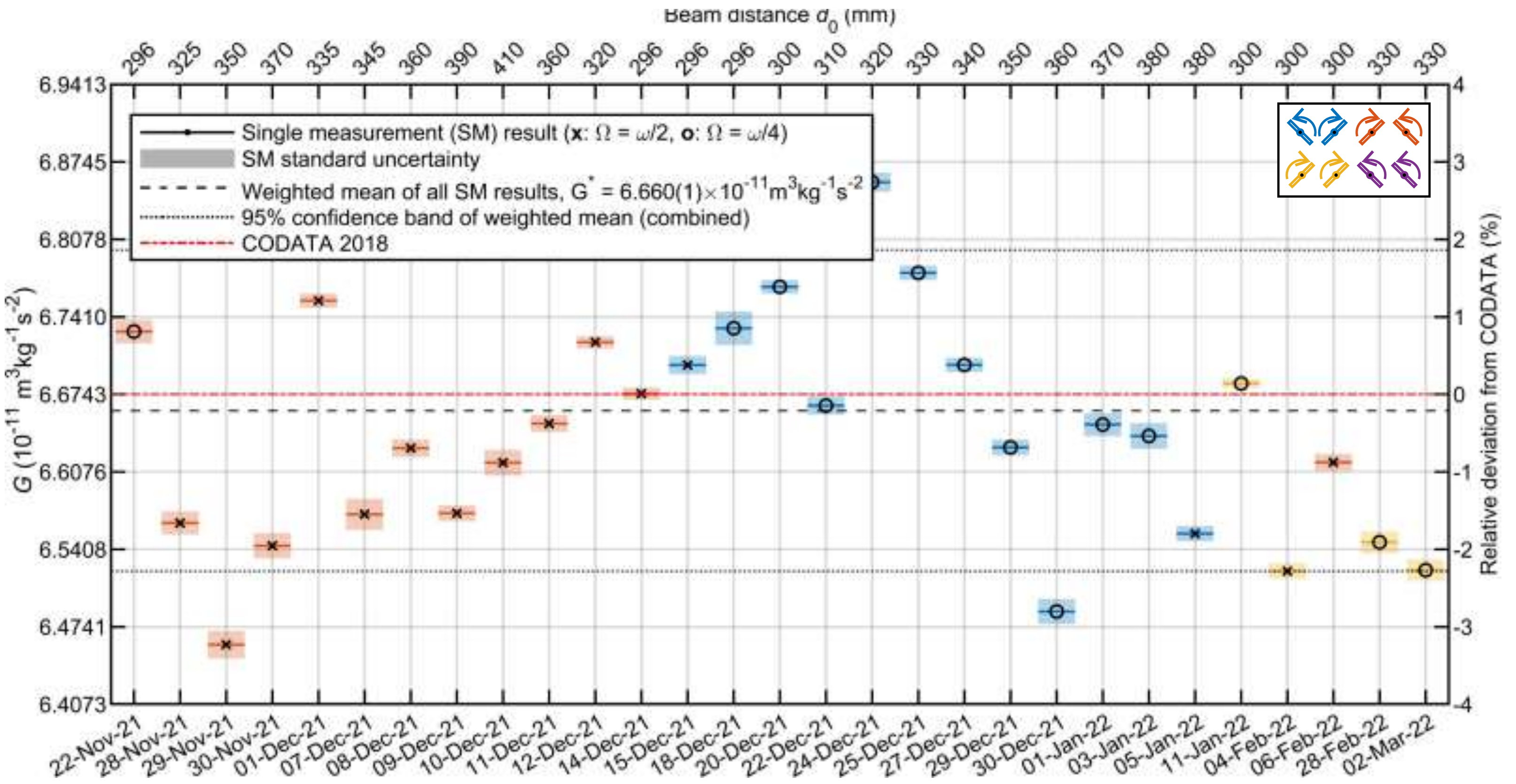



### Fourth harmonic: $\omega_{\text{rot}} = \frac{\omega_{\text{res}}}{4}$



# Dynamic Gravity, Results for Rotating Bar Transmitters

- **Distance Dependency**
  - $u_d \sim \frac{1}{r^5}$
- **Determination of *G***
  - $G = 6.66(7) \cdot 10^{-11} \, \frac{\mathrm{m}^3}{\mathrm{kg\,s}^2}$
  - 0.2% Deviation from CODATA
  - ~1% Accuracy
- **Energy Flow**
  - Up to 3.75 $10^{-18}$ J/s
  - $10^{22}$ times greater than what is quoted in text books for gravitational *waves*

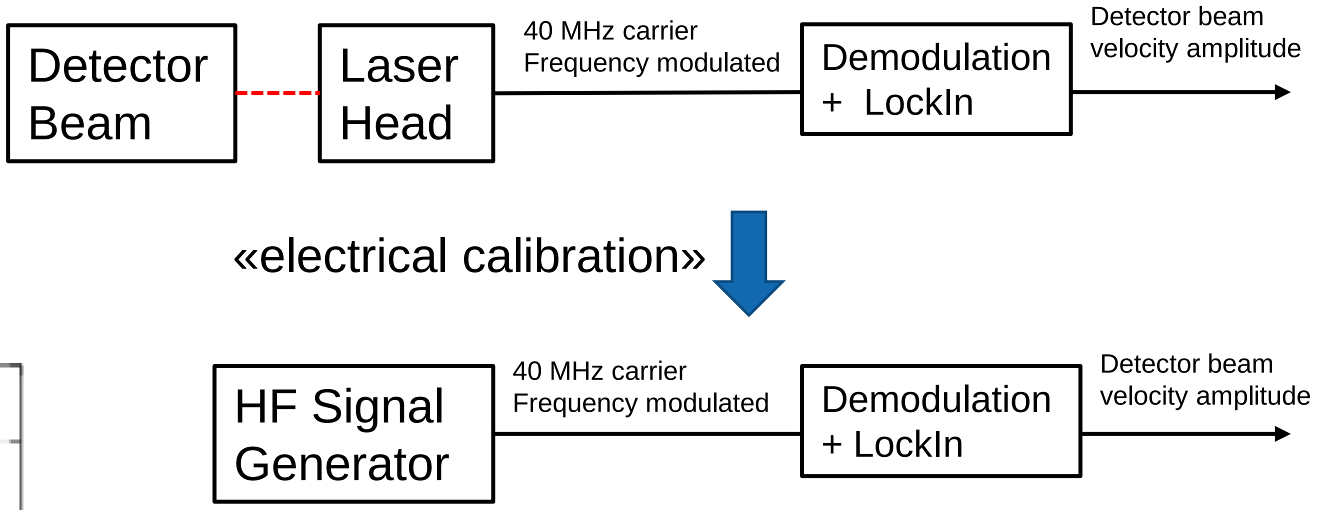


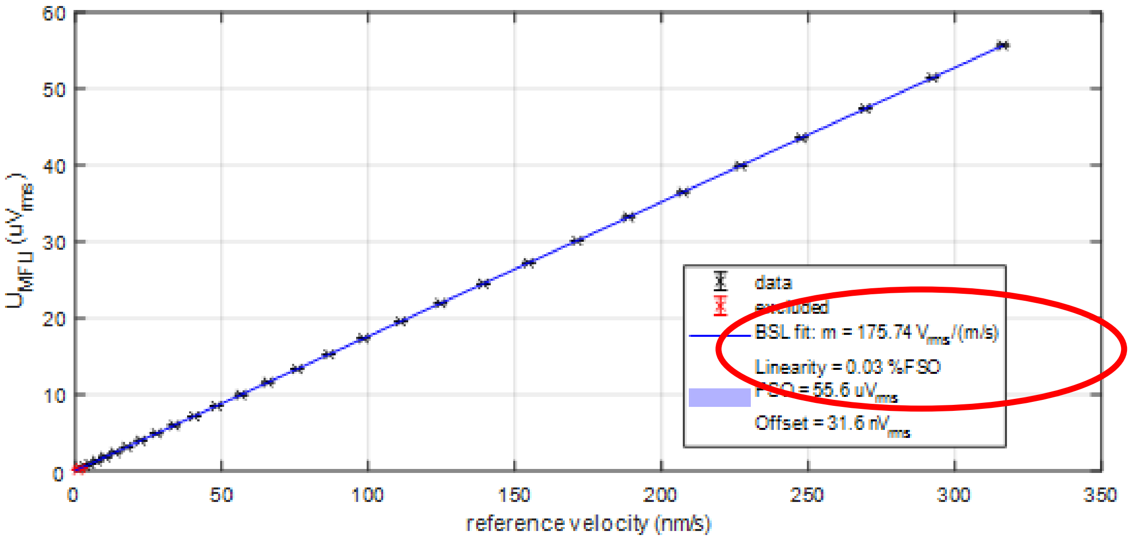

In Review with Communications Physics

# 4. Current Efforts and Improvements

1. More gravitationally induced amplitude -> 20x20mm rotating W bars
2. Individual calibration of the laser measurement chains

*electrical calibration*
feeding a known artificial carrier and Doppler frequency signal into the Laser demodulators and measuring the LIA outputs



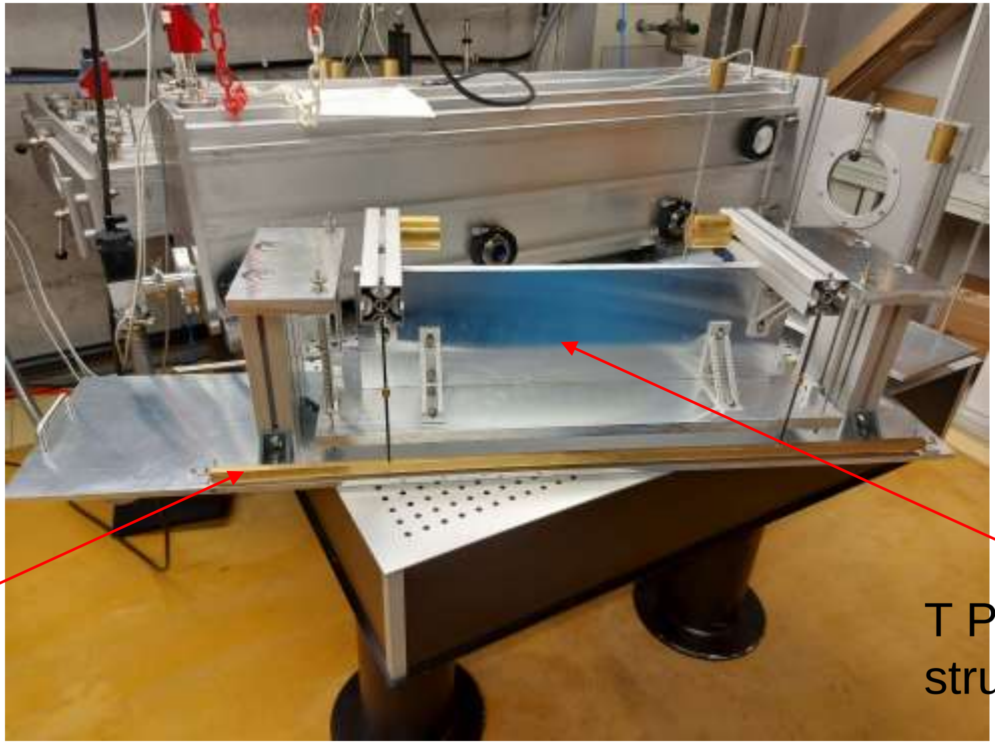




Doppler Shift

$$\Delta f(t) = \frac{2v(t)}{\lambda}$$

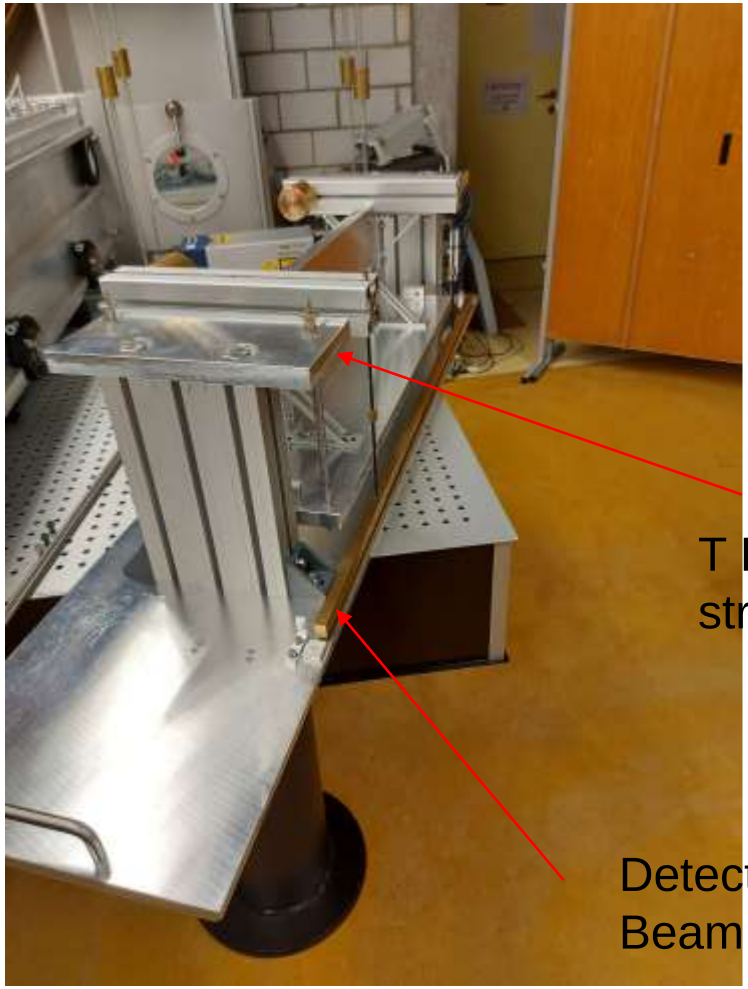
# 3. Improved vibration isolation of DB from Transmitter motion:

## 3.1 Passive vibration isolation stage in detector chamber (Factor 5-7)



Detector Beam

T Plate structure



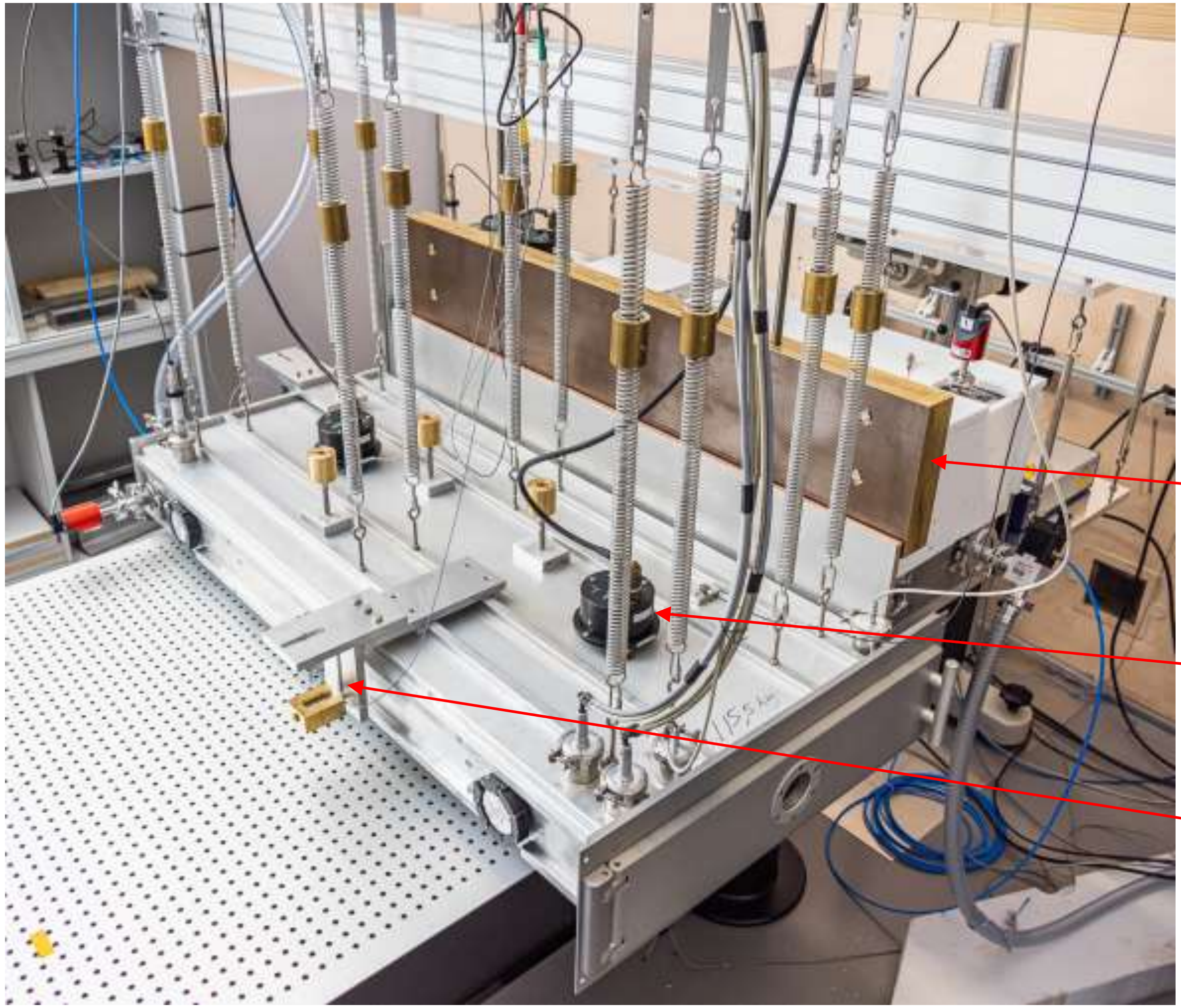
T Plate structure

Detector Beam

The detector beam inside the vacuum chamber is hanging from a T-plate structure of about 20kg, hanging on 4 springs

# 3. Improved vibration isolation of DB from transmitter motion:

## 3.2 Active vibration minimization of transmitter chamber (Factor 2)



The remaining motion of the transmitter chamber is cancelled by an active system, Consisting of Kinemetrics Episensor accelerometers and stacked linear piezoactuators (PI)

Brass shielding plate

6 accelerometer channels

5 Piezo actuators

# 4. Neutron tomography at NEUTRA (PSI, Villigen, Switzerland)

- Transmittance through 28.3mm of W
  - $10^{-38}$ for 150 keV Xrays
  - 0.015 for 25 meV neutrons
- Standard imaging set-up MIDI@NEUTRA beam line
- 30 µm Gadox (Tb-doped) scintillator screen
- High resolution tomography for 67mm end parts and Low resolution tomography for whole rod
- Mean sample-to-detector distance approximately 17mm

20 x 20 x 500m
Tungsten Rod

Conical Recess

**Results**

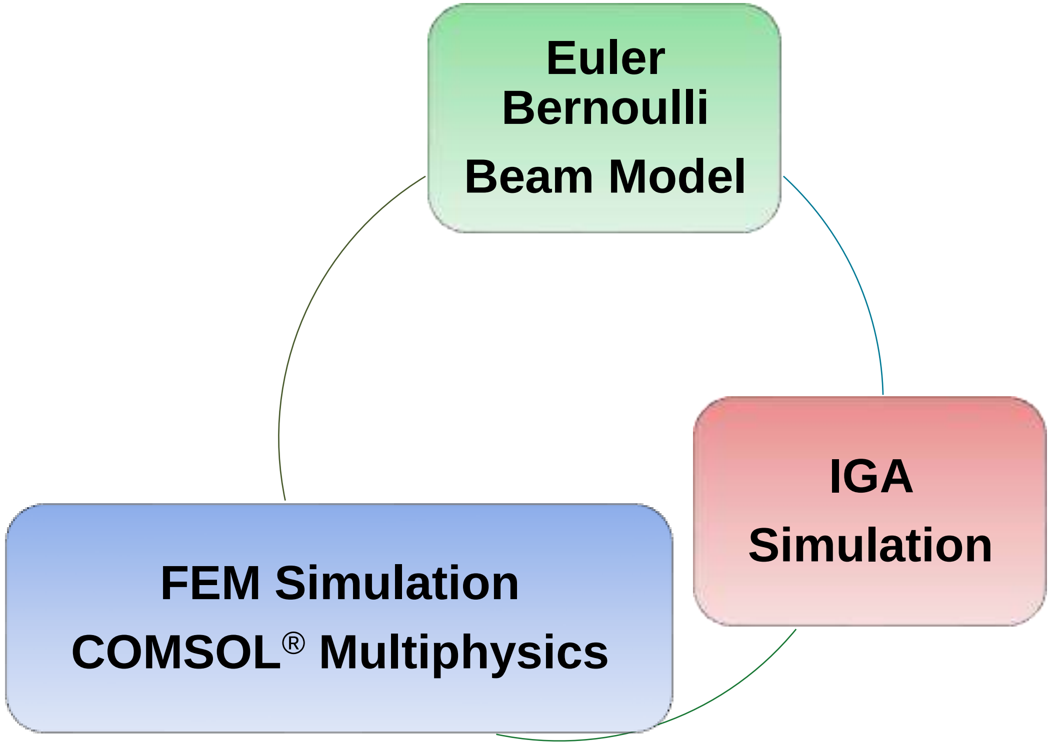
The spatial resolution of the high-resolution and low resolution combined tomographies is < 100 µm ->
A void of this size corresponds to a mass ratio of $10^{-8}$ for the 67mm of the transmitter bar closest to the detector

Bars can be modelled as homogeneous!

# 5. Improvement of Simulation of the Rotating Bars Experiment

- Experiment and Simulation validate each other
- Combining 3 Approaches
  - Analytical model and numerical integration
  - Commercial Finite Element model
  - Isogeometric (IGA) (FEM) model
- Used as reference for the computation of the gravity constant $G$
- Simulation needs to be highly accurate, i.e. orders of magnitude more accurate than the experiment:
  Accuracy goal for velocity amplitude: $\sim 0.1\ \mathrm{ppm}$

**3 Detector Beam Models for the Gravity Experiment**



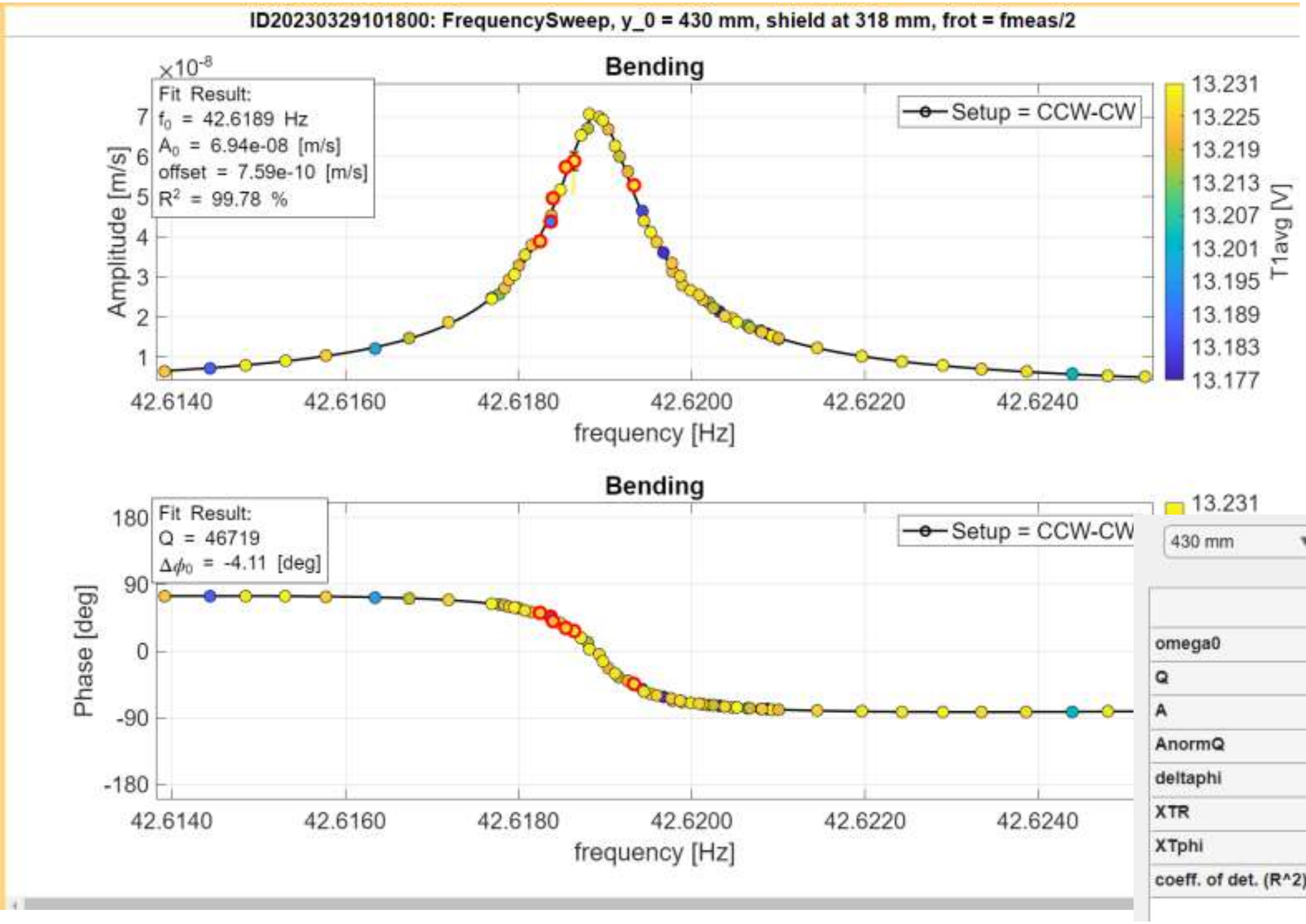
# Some results: 20x20mm rotating bars (2,1,-1)

**Typical run:**
70 points on resonance curve ( random ) -> > 4 days
Per point we record 500 points in time / the last 200 are averaged
3 Detector beam lockin channels
7 accelerometer lockin channels (2 on DC, 5 on TC)
Temperatures, pressures
Jitter

Figure:
Raw data (~10hrs) at
- 3 Lockin Amplifiers
  measuring gravitation
- DC acceleration

# Some results: 20x20mm rotating bars (2,1,-1), April 2023

Complex Fit and Fit Results




Theory:

FEM/IGA Results:
A/Q= 1.487 $10^{-12}$ m/s

Euler Bernoulli:
A/Q= 1.500 $10^{-12}$ m/s

Experiment:
A/Q= 1.486 $10^{-12}$ m/s

430 mm | 318 mm | CCW-CW | Bending | 1/2

| | Value | lower CI | upper CI | unit |
|---|---|---|---|---|
| omega0 | 267.78246 | 267.78245 | 267.78247 | rad/sec |
| Q | 46719 | 46688 | 46769 | - |
| A | 6.9416e-08 | 6.9393e-08 | 6.9436e-08 | m/s |
| AnormQ | 1.4858e-12 | 1.4844e-12 | 1.4869e-12 | m/s |
| deltaphi | -0.0717 | -0.0724 | -0.0711 | rad |
| XTR | 7.5938e-10 | 7.5640e-10 | 7.6290e-10 | m/s |
| XTphi | 0.0987 | 0.0713 | 0.1319 | rad |
| coeff. of det. (R^2) | 99.7812 | | | % |

# 5. Conclusions and Outlook

## Conclusion

- Improved **dynamical gravity experiment** at 42 Hz with **full quantitative comparison** between measurement and theory
- Current state:
  - Good agreement between theory and experiment with **deviation ~ 0.1%**
  - **Uncertainty ~0.1%**

    **(to be confirmed with full error analysis )**
  - Max. ~300 nm/sec for excitation with two rotating 2x2cm bars
  - Neutron tomography characterization of samples (no holes of size >100µm)
  - Mechanical crosstalk/signal ratio improved by more than 100x
  - Improved FEM Modelling with $10^{-4}$ accuracy

# 5. Conclusions and Outlook

## Outlook

- **Improve**
  - Reduce temperature sensitivity by optimized detector beam
  - Distance measurement
  - Continuous improvements on all the aspects discussed
  - Double lock-in technique to relate the velocity only to $c_{Light}$ and frequency

- **Investigate: It is getting more and more interesting!**
  - G and distance curves
  - Gravitational shielding
  - Phase behaviour
  - Frequency influence on gravitation
  - Influence of other fields: Electric fields at different frequencies, quantum devices,…
  - Any further suggestions?
  - Collaborations?

ETH zürich

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Thank you very much for your time and attention!

Prof. Jürg Dual
dual@imes.mavt.ethz.ch

ETH Zürich, 8092 Zürich https://expdyn.ethz.ch/

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